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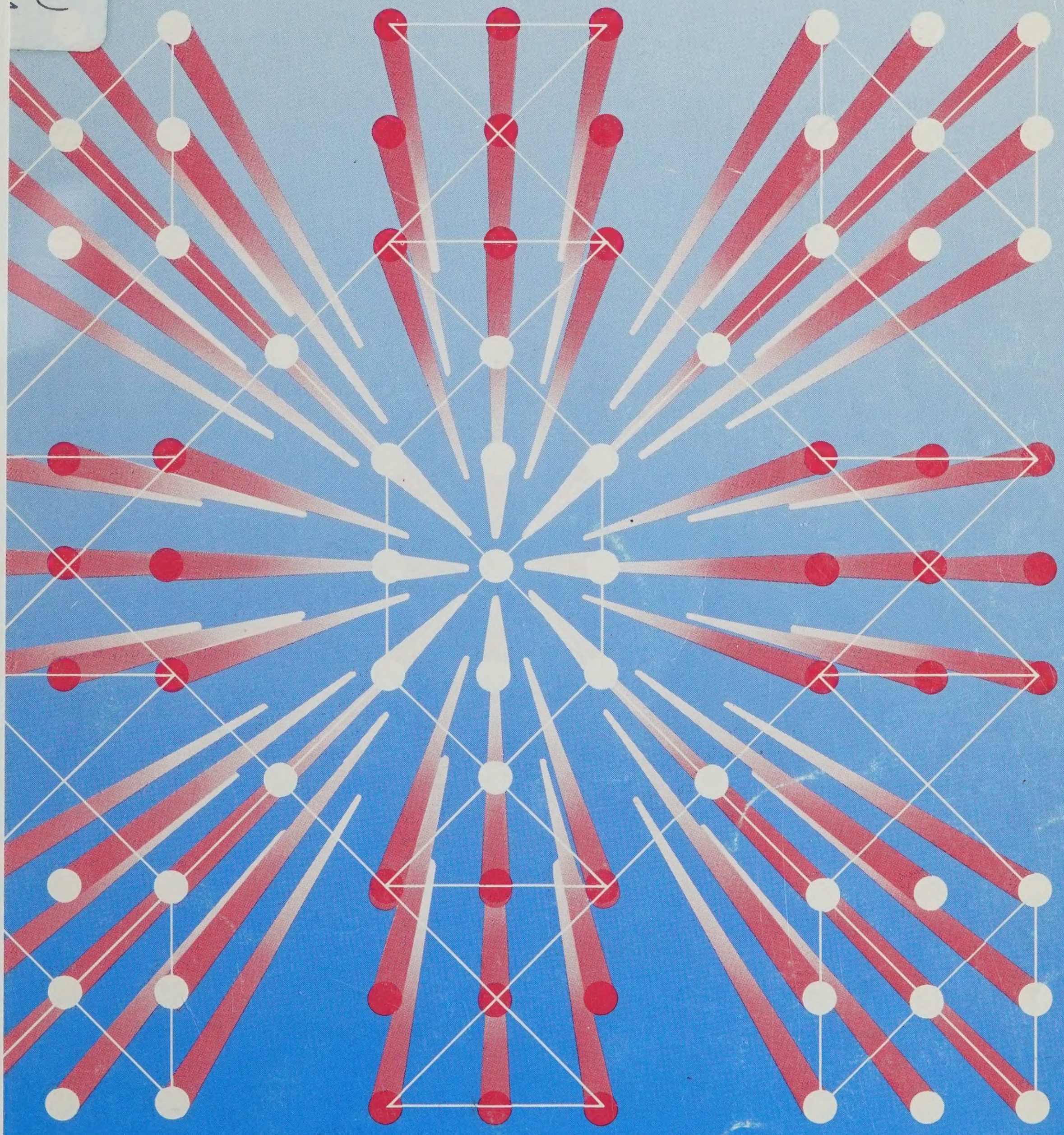

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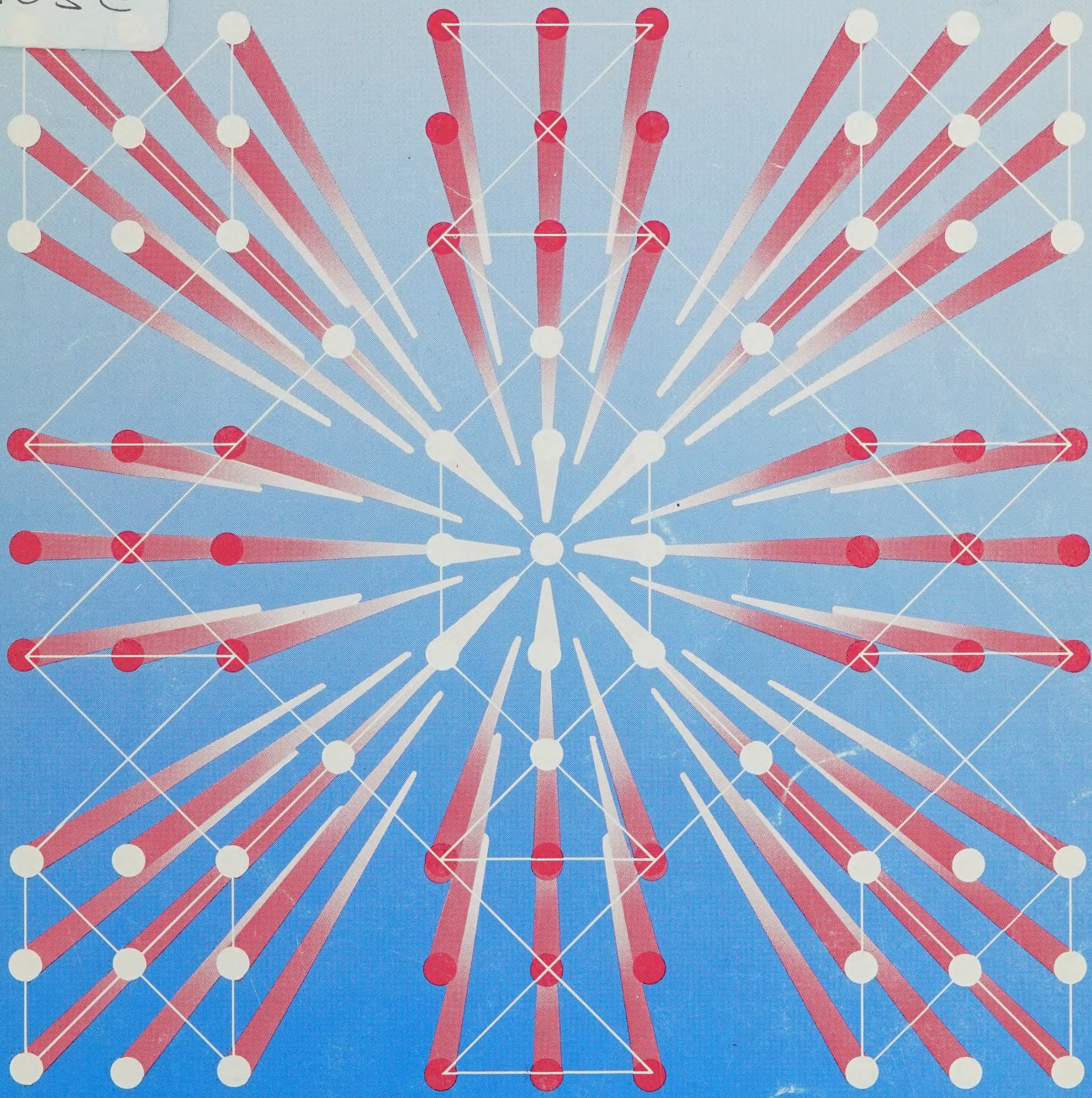

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Industrial Productivity and Research and Development Indicators

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PREFACE

This paper describes the conceptual and statistical issues involved in the measurement of productivity change. In particular it examines the use of Research and Development Capital as a factor of production.

Science and technology indicators may be defined as statistics which measure quantifiable aspects of the creation, dissemination and application of science and technology. As indicators, they should help to describe the science and technology system, enabling better understanding of its structure, of the impact of policies and programs on it, and the impact of science and technology on society and the economy.

Industrial Productivity and Research and Development Indicators is one of a series of background papers on science and technology indicators to be published by Statistics Canada. The purpose of the series is to describe the theoretical development, limitations and application of various statistics suggested as indicators of science and technology.

Current indicators of Canada's scientific and technological activities include:

- expenditures on research and development;
- federal government scientific activities;
- personnel working in science and technology;
- Canadian research output (citations);
- Canadian patented inventions;
- international payments and receipts for technology;
- trade in selected commodities.

Statistical tabulations of the indicators will be released in **Science and Technology Indicators,** Catalogue No. 88-201, an annual summary; **Industrial Research and Development Statistics,** Catalogue No. 88-202 (Annual); **Resources for Research and Development in Canada,** Catalogue No. 88-203 (Annual); **Federal Scientific Activities,** Catalogue No. 88-204E (Annual) and in a monthly service bulletin, **Science Statistics,** Catalogue No. 88-001.

A list of the proposed background papers is included at the end of this publication. These papers represent the opinions of the authors and do not necessarily represent those of Statistics Canada. Comments are invited and should be addressed to Karen Walker of the Science and Technology Statistics Division.

This report has been prepared by Professor Jeffrey Bernstein of Carleton University, Ottawa.

Martin B. Wilk
Chief Statistician of Canada

TABLE OF CONTENTS

INTRODUCTION

The slow growth rates in output and productivity and the persistence of high unemployment rates have generated renewed interest in the sources of output growth. Because it has been established that technical change is a significant element among output growth determinants, a great deal of this interest has centred on the rate, timing and diffusion of technological progress.

Although technical advance generates benefits from output expansion, production cost reduction, and product variety, there are also significant costs. There are the costs of developing the new products and processes. There are adjustment costs as certain types of labour and physical capital become obsolete, perhaps resulting in greater unemployment and earlier retirement for certain worker groups, and in shutdown or extensive structural change for particular firms and industries.

A major concern of researchers and policy-makers has been the development of indicators pertaining to productivity and technical change. For the policy-makers, these would indicate the major firms, industries or regions undertaking technical advances. They could also measure the rate at which technical change is occurring, and which outputs are being produced by a more intensive application of new techniques. Moreover, it would be possible to determine the diffusion of technological change throughout the economy.

The relationship between output growth and technical change has been analyzed in many studies. However, traditionally the focus has been rather narrow in the sense that estimates have indicated measures of technical advance used but not necessarily developed by the specific firm, industry, region or country. Any technological progress that occurred was considered to be exogenous. Very little is known about the innovation process and the type of indicators that can be measured. Unanswered questions remain, or are just beginning to be answered, relating to the interaction between the production of knowledge and the other, general production processes.

The major purpose of this report is to analyze (for the non-specialist reader) the type and measurement of indicators relating to technological change. We first focus on the relationship between productivity growth and technological change. We clarify aspects of the total factor productivity growth index and show how it emerges from a production process. Our concern with this index then centres on the measurement problems. The historical evolution of this concept is discussed in Appendix I where we describe how refinements and extensions have taken place since the 1940s.

The second general focus is on the knowledge production process, and how the measurement of research and development (R&D) can summarize this process. Various technological change indicators based on R&D data are evaluated and compared. Specifically, we analyze indicators showing the relationship between R&D and the other factors of production: labour, physical capital and intermediate inputs.

Finally, we discuss the numerous problems associated with measuring the R&D input. Undertaking R&D investment takes time, and consequently there are significant lags between expenditure on R&D and the 'delivery' of useful new information. In addition, there are spillover effects in the production of knowledge. The R&D input does not depend solely on the activities of the firm or industry itself, but on the activities of many producing units operating in many different industries.

Chapter 1

PRODUCTIVITY AND TECHNICAL CHANGE: THE CONCEPTUAL FRAMEWORK

Phrases like low productivity, insufficient technical change, and slow output growth are often used in characterizing the current state of various industries, regions and the general malaise of the Canadian economy. Yet one is given the impression that, outside of a narrow group of specialists, there is only a cursory understanding of these terms and their interrelationships. The purpose of this section of the study is to define these concepts by placing them in a conceptual framework; their development from a historical perspective is presented in Appendix I.

The analysis of production is the starting point. From an economist's viewpoint, the production process is a transformation of quantities of different inputs (or factors) into quantities of various outputs (or products). This process takes place by means of a particular technology. Thus the basic ingredients of production are inputs, outputs and technology.

The process can be described in simple or more elaborate terms. A farming operation may be measured as inputs of seeds, labour and land to produce corn. More complicated examples could introduce additional inputs at various times to produce many outputs. Telecommunications is an interesting case: various types of labour are combined with switching equipment, loops, microwave towers, trunk lines and satellites to produce telephone calls, broadcast services and for data transmission. Moreover, each of these aggregate output classifications can be broken down in a number of ways.

There are three general production-related problems that interest economists. The first revolves around **the degree to which the factors of production can be used as substitutes for one another** to produce given outputs. The second set of issues relates to the **nature of the expansion of outputs** when all inputs change by a specific percentage. The last topic concerns the **rate of technological (or technical) change** (technical and technological are used synonymously). Factor substitution possibilities, output expansion effects, and technological change are the focus of the current analysis of production. This chapter is principally concerned with the last of these three topics.

Technological change has played an important role in particular industries and in the Canadian economy generally. To understand and define this role, the major indicator is called **total factor productivity (TFP) growth.** TFP growth is defined as the **common rate by which all outputs can grow** over time with all the inputs held fixed, as technological change occurs. There is another way in which TFP can be defined. Consider all outputs growing by some common rate. This growth must arise, basically for one of two reasons - inputs are growing or technology is changing. Hence, the **difference between the common rate of growth of the outputs, and the common rate of growth of the inputs** must represent the 'residual' component representing technical advance. This difference is called total factor productivity growth. It is the amount by which outputs can grow in excess of the input growth rate.

Other productivity indicators have been developed and are still in use. These are **partial productivity indicators** because they **focus on output growth in relation to a particular factor of production.** The most common partial productivity indicator is defined as output-per-worker (or output-per-manhour). This is called labour productivity.

In general discussions among non-specialists, labour productivity measures are still popular indicators for a number of reasons. First, the process of wage determination is based, in part, on labour productivity gains. Second, labour payments represent approximately 70% of the costs of production, and therefore variations in the labour productivity growth rate are a significant element in cost increases and decreases. Consequently, labour productivity growth leading to wage or price changes is an important element in raising the real living standard of individuals in society.

Although measuring the growth rate of labour productivity is important, we must remember that there are many resources besides labour which enter into the production process. Hence it seems preferable to measure productivity in a way that compares output growth with the combined growth rate of all factors of production. For this reason total factor productivity growth is a superior indicator to the growth rate of labour productivity.

There are many instances when total factor productivity growth and labour productivity growth may not even vary in a direct relationship. Suppose output is growing at a relatively higher rate than labour input. In addition, assume that all non-labour inputs are growing at a higher rate than output. In this case labour productivity growth is rising, while total factor productivity growth may be falling. The latter indicator highlights that the use of all scarce resources is growing at a rate in excess of the outputs of the production process.

Chapter 2

THE MEASUREMENT OF TOTAL FACTOR PRODUCTIVITY GROWTH

A measure of total factor productivity growth may be derived from indices reflecting the technological and behavioural conditions of the various economic entities (firms, industries, regions, etc.) under consideration. In the following sections the type of data needed for the construction of labour, capital, intermediate input and output are discussed. These are the basic elements used in the determination of total factor productivity growth.

Labour Input

In total factor productivity growth studies, labour input is computed by measuring the labour cost in constant prices. This index number is constructed from data on hours worked and compensation per hour (i.e., the wage rate). The data on hours worked and compensation per hour for each industry can be broken down in a number of ways. For example, labour can be disaggregated by sex, age, education, class of worker and occupation.

In measuring the labour input, hours paid have often been substituted for hours worked, since most employment surveys provide data on hours paid. Hours worked is, however, a more appropriate measure. The growing numbers of hours that are paid but not worked due to leaves such as vacations and illnesses would lead to an upward bias in the growth of labour input if data on hours paid were substituted.

The compensation of the labour input in relation to actual hours worked is required to form an index of labour input. Generally, compensation data is in the form of compensation per person rather than compensation per job. One method of conversion is to divide the average number of weeks paid per year for each worker category by 52. This ratio provides an estimate of the number of jobs per person in each worker category. Thus by dividing compensation per person by the number of jobs per person, we arrive at compensation per job.

Some studies use annual compensation rather than the combination of hours worked and compensation per hour. The former is not a particularly good measure for the construction of labour input. The reason is that annual labour compensation is the product of annual hours and hourly compensation. Annual compensation may differ among different worker categories, and within each category over time. These differences may be the result of either changes in hours worked, compensation per hour or both.

Capital Input

The measures of capital input for the various industries are index numbers constructed from data on the services of the capital stocks and rental rates for capital services. At the conceptual level these indices are analogous to the measures of labour input which we have just described. Capital input is defined as the services from the capital stock, just as labour input involves the services from the labour force. Capital services are compensated at rental rates in a similar fashion to the compensation of labour services at wage rates. Hence a possible approach to the construction of measures of capital input would be to gather data on lease transactions in capital services. Indeed, in some countries, this provides the basis for measuring capital services associated with the use of dwellings. Data on rental rates for tenant-occupied dwellings are used to measure the rental rates for owner-occupied dwellings. Data on the total stock of dwellings are used in constructing measures of the housing services.

A vast amount of capital used in contemporary economies involves leasing markets. For example, most types of land and structures can be leased, and leasing markets exist for many types of equipment: transportation, construction, electronic, furniture, etc. However, little work has been done on the compilation of data from lease transactions. Thus the construction of measures of capital input based on procedures analogous to those adopted for labour input is not feasible. An alternative method is to compute the level of capital stocks at each point in time from data on investment flows up to that date. Similarly, rental rates required for the indices of the capital factor of production can be inferred from data on the prices of investment products.

Just as the labour input can be disaggregated by demographics and industry, capital can be disaggregated by type, sector and industry. For each industry, capital can be cross-classified by type (e.g., land, inventories, non-residential structures, residential structures, producers' durable equipment, consumers' durable equipment), and by sector (e.g., corporate business, unincorporated business, households and institutions).

The first task in constructing measures of the capital stock involves a knowledge of investment (capital expenditures in constant prices), and the depreciation rate for each type of capital. The capital stock in any period equals the sum of investment and the undepreciated capital. In the case of the declining balance pattern of depreciation, the latter magnitude equals the product of one minus the depreciation rate times the capital stock in the previous period.

The second task is to construct rental rates for the capital input. The rental rate is usually thought of as consisting of two components: a return on the funds tied up in the capital, and a return on the consumption of the capital. Thus the rental rate is the sum of the return to and the return of capital. It must be recognized that the return to capital is after tax, so the various income, capital and property taxes must be considered in computing the rental rates.

Intermediate Input and Output

At the economy-wide level of aggregation, the definition of output is based on final product demand (namely consumption, investment, government, and expenditures on net exports). The corresponding definition of inputs is based on value added by the primary factors of production (namely capital and labour). The value of final output equals the value of primary inputs. However, at the industry level, output is produced by means of the primary factors, plus intermediate input. Thus the value of output, at the industry level, is equal to the value of the primary and intermediate inputs.

The necessity of including intermediate products as an input can be easily illustrated. Consider a retail garment outlet. The owner may choose to have one of the employees display the wares in the window or the owner may contract with a window display firm to dress up the windows. The former is part of the labour cost, while the latter is an intermediate input. If the intermediate input is ignored in the calculation of total factor productivity growth then, in the contracting case, total resources used in garment retailing will not be accurately reflected. The growth rate of total factor productivity would then be overstated.

The intermediate input is an index number based on the quantities of the products used as inputs in the production process, and the prices of these products. The basic difficulty is to trace the input-output flow in the economy in order to determine the intermediate inputs. It is also important to recognize that the prices attached to the intermediate inputs, used to arrive at the intermediate input index, are the purchase prices (i.e., including indirect taxes and margins).

Output measures play a dual role in the calculation of total factor productivity growth. Outputs are simultaneously sources of funds (revenues) and uses of funds (intermediate input costs). As the source of funds, for a producing unit, the value of output is measured net of indirect business taxes and of margins associated with the deliveries of the intermediate input. These latter components are considered part of the prices of the intermediate input, and hence there would be double-counting.

We have described the data on prices and quantities of output, primary and intermediate inputs. With these measures, it is possible to construct an index of total factor productivity growth (see Appendix II). For each industry we can measure the growth rate of output minus the weighted average of the growth rates of the inputs, where the weight for any particular input is the ratio of the specific factor cost to the revenue for a given industry. Hence we are able to measure the extent by which output grows at a rate which exceeds the growth rate of the inputs. This measure is referred to as the index of total factor productivity growth.

Chapter 3

RESEARCH AND DEVELOPMENT AND KNOWLEDGE PRODUCTION

The total factor productivity index is an indicator of technological change that represents the effect on output expansion of an exogenous advance in production technique. In sum, this is an important source of growth in the economy, but major progress in developing new products and processes is the result of a specific resource allocation decision. Individuals, firms and other groups devote scarce resources to the production of certain products and processes in order to reduce production costs and increase profits. The purpose of this section of the study is to analyze and develop measures (or indicators) of knowledge production, paying particular attention to the inputs to this process. We first discuss, in general terms, the knowledge production process and, more specifically, the R&D capital input. Second, we focus on the role the R&D input plays in output growth.

The Framework

The production of knowledge, like other commodities, involves an array of inputs ranging through various types of labour, physical capital and intermediate inputs used in the process. It is a distortion to think of knowledge as a homogenous commodity. There are many distinct kinds. Knowledge production is best understood as a multi-input, multi-output production process.

The structure of our framework is even more complicated because knowledge production is embedded in general production. The efficiency of the knowledge production activities of a firm depend heavily on their relationship to other areas of the corporation. For example, whether knowledge output is used may depend on the firm's existing product mix. There are also numerous cases where ideas have emerged and not been put to use because their significance was overlooked. In addition, there are instances where scientists were unable to translate their efforts into operative processes or products.

Conceptually our view is rather straightforward. There is a general production relationship for a firm (or industry or region or country) which illustrates how knowledge and all other outputs arise out of all inputs. Practically, however, in terms of measuring the importance of the knowledge production process, simplifications must be introduced. Let us suppose that we can form a single index of all the inputs used in knowledge production. This technique was used in the measurement of total factor productivity growth, where an aggregate index of labour, physical capital and the intermediate input was developed from a host of different characteristics of the work force, physical capital stock and intermediate products. This assumption presumes that the knowledge production process is self-contained. The development of new products and processes feeds into the other production processes. Now it is possible to summarize knowledge production in the single aggregate index of the knowledge inputs. Let us call this index **knowledge capital or R&D.**

Knowledge Capital and Output Growth

In the basic production framework labour, physical capital, the intermediate input and exogenous technological change were used to produce output. The substance of Chapters 1 and 2 of this report was a presumption of technological change generating output growth. In the current framework, we have labour, physical capital, the intermediate input, knowledge capital (or R&D) and exogenous technological change producing output.

There are two sets of technological change indicators that can be developed. One set relates to the exogenous or autonomous technological change, namely the total factor productivity growth indicator which we have already analyzed. The purpose of this section is to discuss the other set, the endogenous technological change indicators emanating from R&D capital.

Since knowledge capital is an input to the production process, the first indicator we can discuss is in the class of partial productivity measures. It is possible to evaluate the contribution of R&D to output growth. In other words, the first indicator relates the **growth rate of output as R&D expands** over time given all other inputs and exogenous technological change. This measure is referred to as the **R&D elasticity of output.** It illustrates the responsiveness of output (in percentage terms)

I

to increases in R&D capital. This indicator operates at the margin (i.e., for incremental changes in R&D). A second measure concerning output can be defined as the **quantity of output produced per unit of R&D.** This indicator is called **R&D (or knowledge capital) productivity,** and it relates to the average quantity of output arising from a unit of knowledge capital.

These two indicators summarize the effect that R&D has on output. It is also conceivable that the converse can arise. Output can influence R&D. Hence we can define a measure which relates the **growth rate of knowledge capital to output growth** over time, given all other inputs and exogenous technical change. This indicator is referred to as the **output elasticity of R&D.** Notice that it is sensible to compute the latter magnitude because the R&D input requirement is a decision undertaken by the firm (or other economic unit). This is not the case for the total factor productivity growth indicator, because in that instance technical progress is exogenous.

In a fashion similar to arriving at the R&D productivity measure or index, it is possible to define **R&D per unit of output.** This is called the **R&D intensity of output.**

Because R&D is a factor of production, not only can we investigate the output expansion effects, but we can also measure the degree to which R&D can be substituted for the other inputs. Indicators can show the factor substitution possibilities. For each of the non-R&D inputs, we can measure **the degree to which R&D is a substitute** for each of these factors over time, given output and exogenous technological change. This indicator is called the **labour (or physical capital, etc.) elasticity of substitution for R&D.** There exists one of these elasticities for each non-R&D input. The major indicators are listed in Chart 1.

CHART 1. Major Technological Change Indicators

Source of Technological Change	Indicator
Exogenous:	
Time	Total Factor Productivity Growth
R&D	R&D Elasticity of Output
Endogenous:	
R&D	Output Elasticity of R&D
R&D	Factor Substitution Elasticity of R&D

Little is known of the magnitude of these elasticities and intensities. Only in the 1980s has work been undertaken to determine the output elasticity of R&D and the various substitution elasticities (see Nadiri and Bitros [1980] and Bernstein and Nadiri [1983]). In the 1970s some research investigated the R&D elasticity of output (see Mansfield et al. [1971], Griliches [1973], [1980], Terleckyj [1974], [1980]).

The work relating to the R&D elasticity of output generally assumed a simple production structure (a first order approximation in the logs of the output and inputs). There were usually three inputs: labour, physical and knowledge capital, output augmenting exogenous technological change. Griliches [1973] found for various U.S. manufacturing industries an average R&D elasticity of output at 0.1, while Griliches [1980] for different U.S. manufacturing firms estimated the elasticity to be around 0.07. These estimates included the effects of interindustry and interfirm technology transfers. Griliches in fact observed that for the firms which were more R&D intensive (i.e., higher R&D intensity of output), the R&D elasticity of output was 0.1 and for firms which were less R&D intensive the elasticity was 0.05. This set of results is consistent with Mansfield [1968], who found for chemicals and petroleum an elasticity of 0.12 and Minasian [1969] who found for chemicals an elasticity of 0.11. Terleckyj [1980] in studying a smaller number of U.S. manufacturing industries than Griliches, but over a longer time period (1948-1966), found similar results. Hence there is a body of evidence, both in terms of cross section (many firms, many industries, R&D intensive industries) and time series, that when R&D increases by 1%, output increases by 0.1% for R&D intensive firms and industries.

Turning to the output elasticity of R&D, we find that the magnitudes are much greater than those of R&D elasticity of output. Output exerts a greater impact on R&D than the converse. Bernstein and Nadiri [1983] estimated that, for different firms in the later 1950s to the mid-1960s, the output elasticity was approximately 1. A 1% increase in output generated a 1% increase in R&D. These estimates were based on a more general model than that used to obtain the estimates of R&D elasticity of output. A dynamic cost minimizing model of the firm was used, the technology was represented by a flexible functional form (i.e., a second order approximation), the dynamics arose through adjustment costs for physical and knowledge capital, there were three factors of production, and a system of equations was estimated.

The output elasticity of R&D is important because it illustrates how product demand growth affects R&D. It is significant in terms of policy formulation to be able to determine both the cyclical variability of R&D, and the secular trend. The latter is represented by the long-run elasticity, while the former is captured by the short-run estimate. It is also of interest to investigate the whole set of major influences on R&D, and to see their relative importance. The substitution elasticities illustrate how changes in the various factor prices affect R&D or knowledge capital requirements.

There are at least three reasons why estimates of substitution elasticities are important. First, it becomes possible to determine the manner in which labour and physical capital interact with R&D. For example, as R&D increases do we find that labour requirements diminish while the demand for physical capital increases? Clearly this issue is crucial to various private sector groups in society (labour unions, management) and the government as well. Second, we are able to estimate the response of R&D to changes in the wage rate, the rental rate on physical capital, and the rental rate on knowledge capital. This implies, for example, that when labour becomes a relatively more expensive factor of production, one can estimate the change in knowledge and physical capital associated with the rising wage rate. Finally, in attempting to find the major determinants of R&D, it is necessary to be able to estimate when output or price effects dominate. The reason is that if output or product demand growth exerts a greater influence on R&D than changes in its rental rate, the government may wish to introduce policies which stimulate product demand as opposed to policies which lower the factor price (such as tax credits and allowances, for example). Thus a knowledge of these effects on R&D help in guiding the government towards the correct policy stance in stimulating knowledge capital accumulation.

Research is only beginning to investigate the substitution elasticities. The only work that has estimated the array of these elasticities is by Bernstein and Nadiri [1983]. This research was based on U.S. firms in four industries (food, chemicals, primary metals and non-electrical machinery) for the period 1959-1966. The substitution elasticities (measured as the response of labour, physical and knowledge capital to changes in each of the three factor prices) are presented in Table 1.

TABLE 1. Long-run Price Elasticities of Factor Demands for Four U.S. Industries, 1959-1966

Elasticity(1)	Food	Chemicals	Primary metals	Non-electrical machinery
e^L_{pp}	-.4784	-.4325	-.4738	-.4538
e^L_{pr}	-.5566	-.1423	-.2820	-.1782
e^L_{pl}	1.0350	.5748	.7559	.6320
e^L_{rp}	-.2089	-.0924	-.3435	-.2136
e^L_{rr}	-.4965	-.4980	-.4696	-.4276
e^L_{rl}	.7054	.5904	.8131	.6411
e^L_{lp}	.2778	.2307	.1758	.2945
e^L_{lr}	.5045	.3649	.1553	.2493
e^L_{ll}	-.7822	-.5956	-.3311	-.5438

(1)e^L_{ij} means long-run factor j price elasticity of factor i, with the subscript l representing labour, p means physical capital, r stands for R&D capital, and the superscript L means the long-run. All values of exogenous variables are equal to their mean.

Source: "Rates of Return on Physical and R&D Capital and the Structure of the Production Process: Cross Section and Time Series Evident", J.I. Bernstein and M.I. Nadiri, forthcoming E.R. Berndt and M.I. Nadiri, **Temporary Equilibrium and Costs of Adjustment,** 1983.

We can observe in this table a great deal of similarity among the various industries with respect to the signs and magnitudes of the factor price elasticities. The own price elasticities of physical (e^L_{pp}) and knowledge capital (e^L_{rr}) are negative and similar in value to each other, across the four industries. Roughly, an increase of 1% in the rental rate of one of the capital inputs leads to a 0.5% decrease in its demand. Next we see that physical and knowledge capital are complements in each industry (i.e., E^L_{pr} and E^L_{rp}). This means that when the price of one of the capital inputs increases the demand for the other capital inputs decreases. However, the complementarity is not symmetric across industries. In foods and chemicals, changes in the R&D rental rate exert greater downward pressure on the demand for physical capital, relative to that which a change in the physical capital rental rate exerts on the demand for R&D capital (e^L_{pr}). The converse is true for primary metals and non-electrical machinery. Thus we can observe that there are significant own and cross price elasticity effects. These are usually neglected in treatments of R&D.

Changes in the wage rate illustrate that both capital inputs are substitutes for labour (e^L_{pl}, e^L_{rl}), with the degree of substitution roughly the same for physical and knowledge capital. In other words, when one of the capital inputs becomes cheaper, the demand for labour declines.

Finally, we can observe that for each industry, and for each factor demand, changes in the wage rate elicit (in absolute value) the greatest response. This, of course, occurs because the capital inputs are complements, while each type of capital is a substitute for labour. The results point to the importance of treating R&D capital as an input in the production process. The latter factor (as all others) responds significantly to input price changes and output expansion.

Chapter 4

THE MEASUREMENT OF RESEARCH AND DEVELOPMENT CAPITAL

The measurement of R&D capital input involves two problems. The first pertains to the components of the input and the second concerns the actual construction of the index.

Composition and Construction

First, the components of the R&D capital input are derived from the data on R&D expenditures. In current statistical summaries scientific research and experimental development (R&D) is defined as creative work undertaken on a systematic basis to increase the stock of knowledge and to use this knowledge in new applications. R&D expenditures consist of the wages and salaries of scientists and engineers, the cost of laboratories and associated equipment, and supplies and services needed to operate the R&D establishments.

There are basically two approaches to the construction of the knowledge or R&D capital input index. First, it could be constructed from data on the services of the elements comprising the index (such as scientists, engineers and laboratories) and the rental rates for these services. At the conceptual level these indices would be strictly analogous to the measures of labour input used in productivity studies (see for example Gollop and Jorgenson [1980]). The knowledge capital input is defined as the services from the knowledge capital stock and these services are compensated at rental rates. This is similar to defining the labour input as the services from the labour force, and the labour services are compensated at the wage rates. Thus a possible approach to the construction of the knowledge capital input would be to gather data on lease transactions in the knowledge capital services.

Little work has been done on the compilation of data from lease transactions, and as a consequence an alternative measurement method is used. The second approach is to compute the level of the knowledge capital stock at each point in time from data on R&D investment flows up to that date. The latter constitute the constant dollar R&D expenditures incurred in each year. The price index used to deflate R&D expenditures could be constructed from data on the prices of the elements comprising the R&D expenditures.

Depreciation and Appropriation

The major difficulty in computing R&D capital through the associated investment flows centres on the nature of the integration of these flows over time. There are two problems related to this procedure; depreciation and appropriation. First, like physical capital, knowledge capital depreciates. For example, knowledge can depreciate because ideas which were thought to be correct can be supplanted by further research. In addition, better products or procedures can render existing ones obsolete. There is some evidence that the depreciation rate for R&D capital exceeds its physical counterpart, with little of the original R&D remaining past 10 years.

The second problem related to the construction of knowledge capital through R&D investment flows is the existence of spillovers. Knowledge capital for any single firm does not depend solely on its R&D investment but on the investment of other firms (which may or may not be in the same industry). The construction of an appropriate knowledge capital input index must take into consideration the interaction between individual firm R&D investment levels.

The spillover issue arises from the difficulty of a firm undertaking R&D investment to exclude other firms from its use. The R&D investor may not be able to prevent competitors and other firms and individuals from obtaining the benefits of the investment without paying for them. The ability to exclude involves the use of scarce resources. In the case of the development of knowledge capital exclusion costs are excessive, so that the benefits spillover to others in society. The implication is that if the R&D performer is not able to prevent 'free-riding' on the R&D, then the performer may not be able to earn a sufficient return on investment. The incentive to undertake the R&D investment is diminished, and society may be facing a situation of underinvestment in R&D activities. Measuring the spillover effects is quite complicated, but it is important in order to attain adequate R&D indicators, and to distinguish between private and social rates of return on knowledge capital.

It is important to clarify the notion of R&D spillover or externality. When a firm purchases physical capital, embodied in that capital is the R&D undertaken by the selling firm. This capital is part of the intermediate input index of the purchasing firm. Hence this index will reflect the capital investments performed by the selling firm to the extent that these improvements have been reflected in the market prices of the physical capital. If market prices fully reflect the benefits of the R&D then no spillover has occurred. All that has taken place is the diffusion of the innovation. Spillovers cannot be said to exist unless market prices have not completely captured the benefits from R&D. Spillovers are the ideas borrowed by firm i from the R&D of firm j, and they do not have to be related to input purchase flows. The telecommunications equipment industry and the computer manufacturing industry may not buy much from each other, but may be undertaking similar R&D investment and hence benefiting much from each other's inventions and innovations.

Firms operating in the same industry produce related products with similar technologies. Clearly, the R&D investment of these firms are mutually useful and can spillover. Estimates of these spillovers provide the intra-industry links. A method to estimate these intra-industry spillovers would be to use the R&D investment of different firms to determine how they combine to form the knowledge capital stocks for the various firms. This approach, although promising, may be severely hampered by a degree of freedom problem. For example, if there are 10 industries, there would be 10 spillover parameters to estimate for each industry. These coefficients in conjunction with the other production-related parameters would generally lead to insufficient data points. A solution would be to pool cross-section and time series data. By gathering information at the firm level (for example), the spillover parameters could be estimated from a model involving time series data for different firms operating within the same industrial classification.

There are also spillover links operating between industries. The determination of R&D investment spillovers is much more complicated once we focus on more than a single industry. Here pooling industry data is not, in general, a tenable solution to the degree of freedom problem. This implies that stronger **'a priori'** conditions must be imposed on the spillover linkages. Raines [1968] used the horizontal product field classification of the National Science Foundation (NSF) to include inputs to an industry's R&D investment and also the R&D expenditures of other industries in the same product field. The use of the input-output table to measure the extent of the spillovers (as found in Brown and Conrad [1967]) is not a promising avenue. This approach implies that the spillovers are related to input purchases, which, in general, is not the case. Alternative data sources and manipulations which may help in limiting the extent of the spillover links are: aggregating Standard Industrial Classification (SIC) categories, aggregating firm industrial diversification data from the Census Manufactures, and aggregating the cross referencing of patents across product fields from the patent data bank PATDAT. It can be argued with respect to using the SIC categories, that the usefulness of one firm's R&D investment to another firm is highest if both are in the same four-digit SIC classification; it is still high if both are in the same three-digit industry group. Clearly, the degree of usefulness diminishes as the level of aggregation of the SIC classification rises. Difficulties occur when we want to extend the borrowing concept between firms operating in different two-digit industry classifications. Here there is no clear connection (e.g., is leather closer to food or to textiles?). The situation is further complicated by the fact that the major R&D performers are conglomerates, sometimes spanning many SIC classifications.

There have been some estimates of the externality associated with R&D investment. Mansfield et al. [1977] conducted an analysis of a small set of major U.S. R&D investment projects during the 1960s. They concluded that the externality was such that 0.77 to 1.50 of the rate of return on R&D investment spilled over to other firms. This externality arose from a few major investments and captured the interindustry effects.

Bernstein and Nadiri [1984] undertook a study of the intra-industry externality associated with R&D investment. They found that for a number of industries, 0.3 of the rate of return on R&D investment spilled over to other firms in the same industry. Investigators, however, are only beginning to look more seriously, both theoretically and empirically, into the spillover problem.

Chapter 5

CONCLUSION

In this report we have described the most important indicators relating to technological change. The conceptual framework and measurement problems have been analyzed. Clearly, an important area for future work is to develop total factor productivity indices, and the output and substitution elasticities related to R&D for different industries.

The R&D related indicators would permit us to determine:

- the response of the accumulation of R&D capital to changes in relative factor prices,
- the response of labour demand and physical capital utilization to firms becoming more R&D intensive, and whether there are significant costs of adjustment,
- the contribution of R&D capital to the degree of returns to scale in production and, also, the degree of substitution between knowledge output and other products,
- the extent to which the private rate of return on R&D differs from the social rate of return, and, also, the source of the externality: whether it is related to R&D undertaken by firms in the same or related industries or in the economy generally.

A number of policy issues emerge from these topics. First, employment implications arise in determining the degree to which R&D capital accumulation is labour-saving or labour-using. It is important to know, for any particular industry, how the relationship between employment and R&D changes over time, and whether this relationship differs among industries. Surprisingly, there is little evidence concerning patterns of factor substitution in firms undertaking R&D activities. However, a knowledge of these parameter values would appear to be an important prerequisite in the design of policies relating to R&D and employment. Although specific magnitudes differ across industries, work that has been undertaken suggests that the elasticity of substitution between physical capital and labour is similar to that between R&D and labour. Of course one must be careful in interpreting these results, but thus far we do not find that massive unemployment results from R&D capital accumulation. Indeed, some work suggests that a capital-saving bias is associated with industrial R&D effort.

Second, it is frequently claimed that Canadian firms do not tend to minimize unit production costs. In other words, scale economies are not fully exploited. Presumably this is one of the reasons that industrial policy stresses the role of export growth. However, the degree of returns to scale under which Canadian firms operate may be understated. Research and development is a significant element in cost reduction as output expands. Nevertheless, most analyses of cost reduction omit the role of the resources allocated to the R&D effort. R&D is a factor of production. As a stock, like physical capital, it contributes to the degree of returns to scale and thereby to the ability of firms to reduce unit costs. Considering R&D in this manner, new evidence illustrates that scale economies appear to be higher, and the contribution of physical capital and labour smaller for R&D intensive firms.

In this report we have noted that a distinguishing characteristic of R&D capital accumulation is that it involves spillovers or externalities. Firms undertaking R&D projects cannot fully appropriate all of the ensuing benefits. This, in turn, creates a divergence between private and social rates of return on R&D investment and provides a rationale for government involvement.

The policy implications of estimating the R&D externality are not solely to provide a rationale for government intervention. More significantly, pinpointing the externality source allows us to measure the wedge between private and social incentives, and thereby determine the degree of intervention. For example, since the source of external economies may have to be subsidized, the difference between the social and private rates of return signify the optimal subsidy. In addition, the externalities may not be symmetrically distributed throughout the economy. This implies that across the board policies to stimulate R&D investment, such as the investment tax credit, may not (by themselves) be appropriate. Policies designed to enhance the incentives to undertake R&D may have to be somewhat more diversified.

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Appendix I

PRODUCTIVITY AND TECHNICAL CHANGE: A HISTORICAL PERSPECTIVE

Prior to 1940 productivity indicators were of the simple labour productivity growth. Total factor productivity growth was first introduced by Tinbergen [1942]. This study consisted of an international comparison of growth in output, input and total factor productivity for France, Germany, the U.K. and the U.S.A. for the period 1870-1914.

Independently of Tinbergen's work, Stigler [1947] measured total factor productivity by weighting the factors of production, namely capital and labour, by their marginal products (i.e., their incremental contributions to output). The Stigler study was for U.S. manufacturing.

In the 1950s several authors, notably Mills [1952], Schmookler [1952], Knowles [1954], Valvanis-Vail [1955], Abramovitz [1956], Kendrick [1956] and Fabricant [1959] found that there was a substantial difference between the growth rates for output and input. This residual was referred to by Abramovitz as the 'measure of ignorance' and the search was on for the elements that would refine total factor productivity growth. In other words, narrow the residual and reduce our ignorance concerning the sources of output growth.

In the 1960s and 1970s a number of refinements and extensions were introduced. Griliches [1960], Kendrick [1961] and Denison [1962] narrowed the residual by sharpening the measurement of the labour input by industrial and demographic characteristics. Denison adjusted the labour input for the U.S. economy as a whole based on data disaggregated by sex, age, education and employment status, but not by occupation or industry. Griliches also looked at the total economy with the labour input disaggregated by sex, education and occupation. Kendrick looked at the labour input disaggregated by industry, but not by demographic characteristics. The framework for the measurement of total factor productivity by means of weighting labour and capital by their marginal products (as developed in the 1950s) was thus extended to the components of the labour input in the early 1960s.

In the latter part of the 1960s and early 1970s the methodology was extended to the capital input. The desirability of disaggregating the capital input by industry, by type, and by economic agent or sector, has been recognized by Jorgenson and Griliches [1967], Christensen and Jorgenson [1969], Kendrick [1973] and Denison [1974]. Denison has developed measures of capital input for the U.S. economy disaggregated by class of asset and by legal form of organization, but not by industry. Kendrick has developed measures disaggregated by industry, but his measures are not cross-classified by asset type and legal form of organization. In their work Jorgenson and Griliches disaggregate the capital input by asset type for the whole U.S. economy, while Christensen and Jorgenson developed a detailed methodology for weighting components of real capital input disaggregated by class of asset and by legal form of organization. This methodology incorporates data on the taxation of income from capital at both corporate and personal levels and data on rates of return and depreciation by asset types and sector. Finally, in the latter part of the 1970s, the number of inputs was expanded to include intermediate factors, and the disaggregation of labour and capital was extended (see Gollop and Jorgenson [1980]).

In Table I1 we present indices of total factor productivity growth developed by Kendrick and Gollop and Jorgenson. This table highlights the importance of disaggregating the capital input and including intermediate inputs into the construction of total factor productivity growth rates.

The first international comparison of total factor productivity growth, subsequent to the pioneering work of Tinbergen, was published by Domar et al. [1964]. This study employed the methodology of Kendrick and included Canada, Germany, Japan, the U.K. and the U.S.A. for the period 1948-1960. A notable feature of this study was the development of separate estimates for 11 different industries within each of the five countries. In 1967 Denison compared U.S. total factor productivity growth with that of eight European countries (Belgium, Denmark, France, Germany, Italy, Netherlands, Norway and U.K.) for the period 1950-1962. This was later extended to 1929-1969 in his 1974 study. The same methodology was employed by Walters [1968], [1970] for Canada and by Denison and Chung [1976] for Japan. Bergson [1974] has compared the growth of Soviet total factor productivity with that of six Western countries (France, Germany, Italy, Japan, U.K. and U.S.A.) for the period 1955-1970. Lastly, using the detailed methodology developed for the measurement of the labour and capital inputs, Christensen, Cummings and Jorgenson [1980] provide an international comparison of total factor productivity growth for Canada, France, Germany, Italy, Japan, Korea, Netherlands, U.K. and U.S.A.,

TABLE I1. Total Factor Productivity Growth Rates, U.S.A. (average annual 1948-1966)

Industry	Kendrick	Gollop-Jorgenson
Metal mining	.0239	-.0335
Coal mining	.0508	.0356
Crude petroleum and natural gas	.0319	.0171
Non-metallic mining and quarrying	.0260	-.0094
Contract construction	.0146	.0137
Tobacco manufacturers	.0108	.0079
Textile mill products	.0395	.0374
Fabricated textile products	.0188	.0077
Paper and allied products	.0249	.0046
Printing and publishing	.0262	.0143
Chemicals and allied products	.0475	.0468
Petroleum and coal products	.0296	-.0208
Rubber and miscellaneous plastic products	.0386	.0269
Leather and leather products	.0165	-.0379
Lumber and wood products excluding furniture	.0341	-.0063
Furniture and fixtures	.0290	.0049
Stone, clay and glass products	.0240	.0132
Primary metal industries	.0157	-.0079
Fabricated metal industries	.0184	.0045
Machinery excluding electrical	.0256	.0102
Electrical machinery and supplies	.0364	.0367

Source: "U.S. Productivity Growth by Industry, 1947-73", F.M. Gollop and D.W. Jorgenson in **New Developments in Productivity Measurement and Analyses,** J.W. Kendrick and B.N. Vaccara (eds.), Chicago, National Bureau of Economic Analysis, 1980.

for the period 1960-1973. In Table I2 we present these latter measures of total factor productivity growth. The table provides average annual growth rates for all nine countries for the period 1960-1973, and for post World War II up to 1960. During the 1960-1973 period for Canada the growth in real product was dominated by the growth in real factor input compared to total factor productivity growth. This result is similar to that for the U.S., Japan and Korea. Conversely, for Germany and Italy total factor productivity growth comprised the major ingredient of real product growth. Lastly, for France, the Netherlands and the U.K. the two components contributed about the same to real product growth.

Recently researchers have not only continued to expand the list of endogenous elements, but have also focused more closely on particular factors. For example, certain components of physical capital and intermediate inputs relate to energy sources as a factor of production (Berndt and Wood [1975], Berndt and Watkins [1981]). These components have been gathered to form a fourth factor in accounting for output growth (capital, labour, materials and energy).

Researchers have also turned their attention to certain types of labour and classes of physical assets related to the development of new products and processes. These ingredients have been defined as the input research and development (R&D) capital (see Mansfield [1972], Griliches [1980], Nadiri and Bitros [1980], Bernstein and Nadiri [1983]).

TABLE I2. Average Annual Growth Rates of Indicators for Nine Countries

Item	Canada	France	F.R.G.	Italy	Japan	Korea	Nether-lands	United Kingdom	United States
					1960-1973				
Real product	.051	.059	.054	.048	.109	.097	.056	.038	.043
Real factor input ...	.033	.029	.024	.016	.064	.055	.030	.018	.030
Total factor productivity	.018	.030	.030	.031	.045	.041	.026	.021	.013
Real capital input ..	.049	.063	.070	.054	.115	.066	.066	.046	.040
Real labour input ...	.020	.004	-.007	-.007	.027	.050	.003	.000	.022
	1947-1960	1950-1960	1950-1960	1952-1960	1952-1960		1951-1960	1955-1960	1947-1960
Real product	.052	.049	.082	.060	.081		.050	.033	.037
Real factor input ...	.035	.020	.036	.023	.047		.027	.018	.023
Total factor productivity	.017	.029	.047	.038	.034		.023	.015	.014
Real capital input ..	.068	.047	.069	.033	.045		.040	.045	.045
Real labour input ...	.011	.003	.016	.016	.048		.014	.002	.010

Source: "Economic Growth, 1947-73: An International Comparison", L.R. Christensen, D. Cummings and D.W. Jorgenson in **New Developments in Productivity Measurement and Analysis,** J.W. Kendrick and B.N. Vaccara (eds.), Chicago, National Bureau of Economic Research, 1980.

Appendix II

THE CONSTRUCTION OF AN INDEX OF TOTAL FACTOR PRODUCTIVITY GROWTH

Following is a construction of an index of total factor productivity growth, using the concepts of output, primary and intermediate input described in Chapter 3.

Consider a production process characterized by

$$\text{(TA1)} \quad y^i(t) = F^i(K^i(t), L^i(t), M^i(t), t) \quad i=1,\ldots,n$$

Where y represents the quantity of output, K represents capital services, L represents labour services, M represents intermediate input services, t represents time. F^i is the production function which has the necessary derivative properties and exhibits constant returns to scale, the superscript represents the particular industry.

Profit maximization in a purely competitive industry implies that,

$$\text{(TA2)} \quad s^i_j = \frac{\partial \ln y^i}{\partial \ln j^i} \qquad i=1,\ldots,n \quad j=K,L,M$$

where s^i_j is the share of the $j^{\underline{th}}$ input cost out of total revenue. Thus for capital $s^i_K = w^i_K K^i/p^i y^i$ where w_K is the rental rate (the factor price of capital), p is the product price, $s^i_L = w^i_L L^i/p^i y^i$ where w_L is the wage rate (the factor price of labour), and $s^i_M = w^i_M M^i/p^i y^i$ where w_M is the factor price of the intermediate input.

Next we can conceptualize the three inputs as aggregates depending on an array of capital, labour and intermediate inputs used in each industry. Under a constant returns to scale technology:

$$K^i = \phi^i (K^i_1,\ldots,K^i_k) \qquad i=1,\ldots,n$$

$$L^i = \psi^i (L^i_1,\ldots,L^i_l) \qquad i=1,\ldots,n$$

$$M^i = \mu^i (M^i_1,\ldots,M^i_n) \qquad i=1,\ldots,n$$

where ϕ^i, ψ^i, μ^i are characterized by constant returns to scale.

We can view the profit maximizing industry equilibrium as a two-stage procedure. The first stage relates to the aggregate inputs, with the industry determining the combination of capital, labour and intermediate inputs which produces the profit maximizing output. The second stage pertains to the determination of the components of the capital, labour and intermediate factors. The equilibrium conditions for the second stage are:

$$\text{(TA3)} \quad s^i_{Kh} = \frac{\partial \ln K^i}{\partial \ln K^i_h} \qquad i=1,\ldots n \quad h=1,\ldots,k$$

(TA4) $$s^{i}_{Lg} = \frac{\partial \ln L^{i}}{\partial \ln L^{i}_{g}} \qquad i=1,\ldots,n \quad g=1,\ldots,l$$

(TA5) $$s^{i}_{Mf} = \frac{\partial \ln M^{i}}{\partial \ln M^{i}_{f}} \qquad i=1,\ldots,n \quad f=1,\ldots,n$$

where $s^{i}_{Kh} = w^{i}_{Kh}K^{i}_{h}/w^{i}_{K}K^{i}$, $s^{i}_{Lg} = w^{i}_{Lg}L^{i}_{g}/w^{i}_{L}L^{i}$, and $s^{i}_{Mf} = w^{i}_{Mf}M^{i}_{f}/w^{i}_{M}M^{i}$.

The latter ratios are the shares of the cost of the input components relative to the cost of the input aggregate.

Now total factor productivity growth is the difference between the output growth rate and an index of input growth rates. In order to determine the difference consider

$$\frac{d\ln y^{i}}{dt} = \frac{\partial \ln y^{i}}{\partial \ln K^{i}}\frac{d\ln K^{i}}{dt} + \frac{\partial \ln y^{i}}{\partial \ln L^{i}}\frac{d\ln L^{i}}{dt} + \frac{\partial \ln y^{i}}{\partial \ln M^{i}}\frac{d\ln M^{i}}{dt} + \frac{\partial \ln y^{i}}{\partial t}$$

$$\frac{d\ln y^{i}}{dt} = s^{i}_{K}\frac{d\ln K^{i}}{dt} + s^{i}_{L}\frac{d\ln L^{i}}{dt} + s^{i}_{M}\frac{d\ln M^{i}}{dt} + \frac{\partial \ln y^{i}}{\partial t} \qquad i=1,\ldots,n.$$

Thus total factor productivity growth is $\ln y^{i}/ t$ since

(TA6) $$\frac{\partial \ln y^{i}}{t} = \frac{d\ln y^{i}}{dt} - [s^{i}_{K}\frac{d\ln K^{i}}{dt} + s^{i}_{L}\frac{d\ln L^{i}}{dt} + s^{i}_{M}\frac{d\ln M^{i}}{dt}] \qquad i=1,\ldots,n.$$

We can refer to $\partial \ln y^{i}/\partial t$ as Divisia indices of total factor productivity growth. It is a measure of technical change. Notice that we have not had to specify the nature of the technical change. In other words the measure is not relegated to a specific kind of technological advance, such as, for example, output augmenting.

Finally, we can write the index of total factor productivity growth for each industry in terms of the input components rather than the input aggregates, by noting that,

$$\frac{d\ln K^{i}}{dt} = \sum_{h} s^{i}_{Kh}\frac{d\ln K^{i}_{h}}{dt} \qquad i=1,\ldots,n$$

$$\frac{d\ln L^{i}}{dt} = \sum_{g} s^{i}_{Lg}\frac{d\ln L^{i}_{g}}{dt} \qquad i=1,\ldots,n$$

$$\frac{d\ln M^{i}}{dt} = \sum_{f} s^{i}_{Mf}\frac{d\ln M^{i}_{f}}{dt} \qquad i=1,\ldots,n.$$

We can refer to these measures as Divisia indices of capital, labour and intermediate inputs.

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